Chapter 1. Introduction

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Ozone (O_3) is the triatomic form of oxygen. It is a key atmospheric trace gas that is present everywhere in the atmosphere and is most abundant in the stratosphere. The abundance of ozone in the stratosphere is largest in the region between roughly 15 and 35 km, which is referred to as the stratospheric ozone layer. This stratospheric ozone layer (Box 1.1) plays many important roles in the Earth system:

- It protects the lower part of the atmosphere (the troposphere) and the Earth's surface from damaging, or "harsh" ultraviolet[1] (UV) radiation from the sun;
- It influences the chemical composition of the lower atmosphere by altering the amount and type (wavelength distribution) of solar radiation passing through it;
- It changes the temperature structure of the stratosphere and thus influences atmospheric transport and mixing; and
- It contributes ozone to the upper troposphere, where ozone is an important greenhouse gas.

Because of many of the above contributions, ozone in the stratosphere and its changes also play a significant role in the Earth's climate system; changes in the ozone layer are influenced by climate change and also contribute to climate change. Appendix A of this

[1] 'Harsh' UV radiation indicates the higher energy portion of the UV spectrum

report contains background information and the answers to some of the most frequently asked questions about the ozone layer (Fahey, 2007).

The focus of this report is on key issues related to (a) the stratospheric ozone layer, including its changes in the past, its current abundances, and expected levels in the future; (b) emissions of ozone-depleting substances and their influences on the ozone layer and climate; and (c) the changes in the ground level UV radiation associated with stratospheric ozone changes.

The chemical processes that lead to the formation of ozone as well as those that remove or destroy it, are distinctly different in the stratosphere from those in the troposphere (Box 1.2). The ever-present balance in the stratosphere between production, removal, and transport determines the abundance of ozone in any given part of the ozone layer. The majority of the removal processes in the stratosphere involve catalytic cycles in which ozone-destroying chemicals are reformed after destroying ozone. This catalytic capability is a key reason why very small amounts of ozone-destroying chemicals introduced into the atmosphere can vastly influence the ozone layer (Box 1.2).

The potential for human-produced chemicals, such as chlorofluorocarbons (CFCs), to deplete the stratospheric ozone layer has received a great deal of attention since the early 1970s. The depletion by chlorine released from CFCs in the stratosphere was expected to be catalytic in nature, in that small amounts of CFCs could destroy vast amounts of ozone. The ozone depletion was predicted to lead to changes in UV radiation at the surface, with potentially major environmental consequences. The anticipated effects of increased UV radiation included increased incidence of skin cancer and cataracts in humans, detrimental effects on ecosystems including the aquatic system, and deleterious effects on materials, such as rubber and plastics. These potential effects were debated and the nations of the world agreed to protect the ozone layer through the 1985 Vienna Convention. Then the ozone hole in Antarctica was discovered in 1985. Investigation of the causes of this annually recurring polar springtime ozone depletion indicated that chlorofluorocarbons and other ozone-depleting chemicals were involved in additional catalytic ozone destruction pathways unique to the extremely cold polar stratosphere. It was also discovered that small particles containing water and nitric and/or sulfuric acid that are found in polar stratospheric clouds (PSCs) play a crucial role in these processes by converting chemically less reactive halogen-containing chemicals into more reactive chemicals, which are more effective in ozone depletion, and involved some catalytic cycles unique to this region.

The Montreal Protocol, a sequel to the Vienna convention, was agreed to in 1987 against the setting of the scientific knowledge at that date. First, the agreements of the Protocol were to reduce CFC emissions and to replace as much of the chlorofluorocarbons by the replacements that could be used in existing devices for most applications. A few applications utilized not-in-kind non-ozone-depleting chemicals. Many of the replacement chemicals still contained chlorine, but overall were less harmful to the stratospheric ozone layer than CFCs; many of these were hydrochlorofluorocarbons (HCFCs). Slowly, even the chlorine-containing substitutes were to be replaced by nonchlorine or bromine containing replacements; many of these are hydrofluorocarbons (HFCs).

During the course of the past three decades of ozone-layer research, it has become clearer that ozone-depleting substances, as well as many of the CFC-substitutes introduced to comply with the Montreal Protocol, are also potent greenhouse gases. Ozone depletion and climate change are distinct issues but are inextricably linked because ozone itself is a greenhouse gas and many of the ozone-depleting gases are potent greenhouse gases. To add to the complexity, changes in the major greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) also influence ozone depletion. Increases in CO_2 lead to a cooling of the stratosphere, which increases ozone in the upper stratosphere in non-polar regions, but decreases ozone in the polar lower stratosphere. The influence of CH_4 and N_2O on the stratospheric ozone layer is dominated by their chemical interactions. Figure 1.1 captures this influence in a schematic form. An assessment of the climate effects of ozone-depleting substances has to consider both of their roles: as chemicals that deplete ozone, and as greenhouse gases that alter climate.

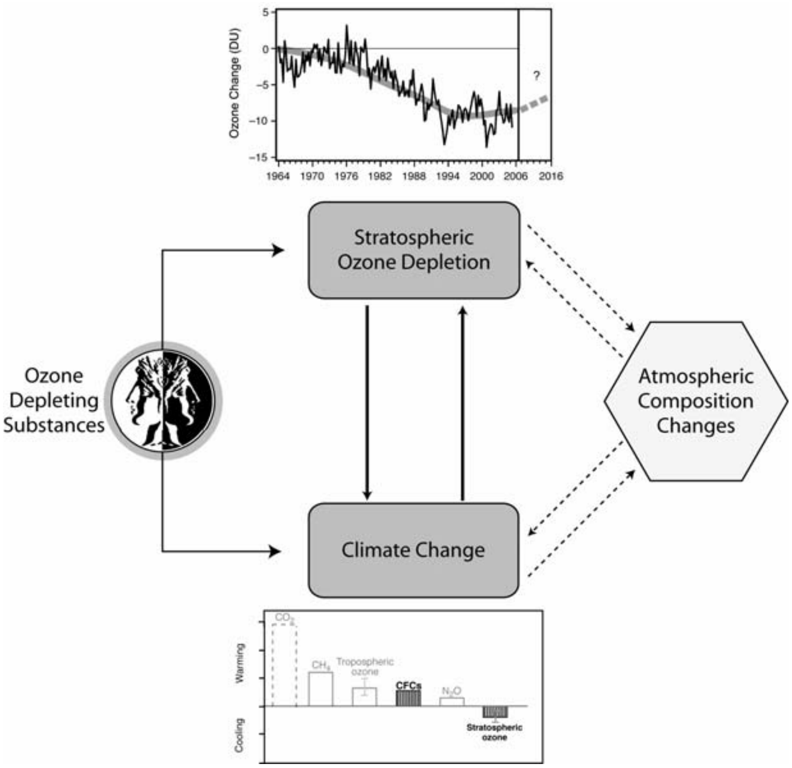


Figure 1.1 The two faces of ozone-depleting substances: their roles as depleting agents of stratospheric ozone, and as greenhouse gases that influence climate. The two roles are further interconnected because ozone itself is a greenhouse gas and because climate change can lead to changes in the ozone layer. The various connections between these two phenomena are shown. A plot of the changes in the observed global ozone illustrates the stratospheric ozone depletion issue. The radiative forcing due to various greenhouse gases, including ODSs, depicts the greenhouse gas issue and stratospheric ozone changes.

Since 1987, there have been many amendments and adjustments to the Montreal Protocol to accelerate efforts to curtail the emissions of ozone-depleting substances (ODSs). These actions have come about in response to our evolving knowledge of the ozone layer and its changes, and have led to a reduction in the emissions and subsequently in the atmospheric abundances of most ozone-depleting substances. Thus, the projected extremely high atmospheric abundances of ODSs and the associated larger-scale stratospheric ozone depletions were prevented from occurring. However, many key questions remain:

- Are the emission controls working as anticipated, *i.e.*, are the atmospheric abundances of ozone-depleting substances declining as expected?
- Is the ozone layer recovering due to decreases in emissions of ODSs as predicted?
- Are the changes in UV occurring as expected with changes in ozone?
- What are the influences of other Earth system changes, *e.g.*, climate and atmospheric composition, on the ozone layer and its recovery from the ODS-induced depletion?
- What are the influences of ODSs, and their substitutes, on other aspects of the Earth system, especially climate?

Because many ODSs have lifetimes of many years in the atmosphere, the depletion of stratospheric ozone is a global problem, and emissions of ODSs anywhere on the globe contribute to the ozone layer depletion. The extent of the ozone layer depletion for a given emission differs depending on the location (*e.g.*, latitude) and time (*e.g.*, season). Therefore, the observed ozone depletion in a given region will not be directly related to the emissions from that region. Yet, it is appropriate to ask: what is the contribution of one nation, or region, to the depletion of the global ozone layer? And, how do the ODSs influence stratospheric ozone, and hence UV, in a specific region or over a specific nation? Of course, it may not be feasible to answer these questions completely at the present time, given our current (and evolving) state of knowledge.

This Synthesis and Assessment Product (SAP) of the Climate Change Science Program (CCSP), SAP 2.4, addresses key issues related to the stratospheric ozone layer, including its changes in the past and its expected evolution in the future. Also, it takes account of the current abundances and emissions of ozone-depleting substances. Further, it synthesizes the best available information on the past and future levels of ultraviolet radiation at the Earth's surface. Lastly, it explores the interactions between climate change and stratospheric ozone changes as well as the ODS changes, and briefly recounts the influence of stratospheric ozone changes on climate change. All of these topics are carried out within the context of the United States of America to distill a regional assessment from current global assessments. More specifically, this document:

- Summarizes current quantitative information on sources (*i.e.*, emissions), sinks (*i.e.*, the removal pathways and their speed), and abundances of ozone-depleting substances and associated uncertainties; describes how the combined influence of chlorinated and brominated ODSs in the stratosphere can be quantified, and how all these are likely to change in the future.
- Discusses levels of ozone in various regions of the stratosphere, including the polar regions, paying special attention to the Antarctic ozone hole.
- Provides information on the past, current, and anticipated future levels of ultraviolet radiation.
- Provides an assessment of the impact of changes in both climate and atmospheric composition on the future of the ozone layer.
- Provides a brief assessment of the contribution of ozone-depleting substances on forcing of climate because these chemicals are also greenhouse gases.
- Describes how these findings relate to human activities, with a particular emphasis on the U.S. Special emphasis has been placed on quantifying the

contributions of the United States of America to the global amounts of ODSs. Further, given the influence that ODSs and substitute chemicals have on climate, the report attempts to calculate the contributions to the relief of climate change via reductions in the emissions of ODSs and switching over to more climate-friendly and ozone-friendly CFC substitutes.

The primary sources of information for this report are the World Meteorological Organization (WMO) / United Nations Environment Programme (UNEP) 2006 assessment on the ozone layer *Scientific Assessment of Ozone Depletion: 2006* (WMO, 2007), and the 2005 Special Report of the Intergovernmental Panel on Climate Change (IPCC) on *Safeguarding the Ozone Layer and the Global Climate System – Issues Related to Hydrofluorocarbons and Perfluorocarbons* (IPCC/TEAP, 2005) and references therein. In addition, this report bases some findings on a few peer-reviewed publications of direct import to this issue that have become available since the finalization of the two international assessments. The report was initiated before the release of the IPCC Fourth Assessment Report (AR4). Therefore, this report does not rely on the IPCC AR4; however, some key pertinent issues from the IPCC report are used in a few instances where updated information was essential. They are noted as such in those chapters.

CHAPTER 1 REFERENCES

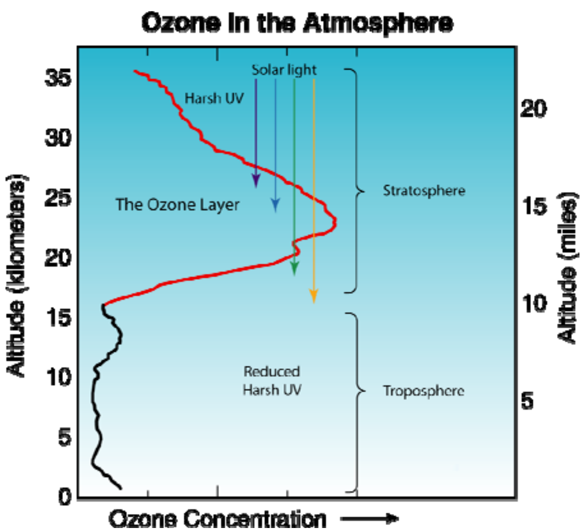
Fahey, D.W. (Lead Author), 2007: *Twenty Questions and Answers About the Ozone Layer: 2006 Update*, in *Scientific Assessment of Ozone Depletion: 2006*, Global Ozone Research and Monitoring Project—Report No. 50, World Meteorological Organization, Geneva.

IPCC/TEAP (Intergovernmental Panel on Climate Change/Technology and Economic Options Panel), 2005: IPCC/TEAP Special Report on *Safeguarding the Ozone Layer and the Global Climate System – Issues Related to Hydrofluorocarbons and Perfluorocarbons*, prepared by Working Group I and III of the IPCC and the TEAP, [Metz, B., L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. de Jager, T. Kestin, M. Manning, and L.A. Meyer (eds.)], 488 pp, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

WMO (World Meteorological Organization), 2007: *Scientific Assessment of Ozone Depletion: 2006*, Global Ozone Research and Monitoring Project—Report No. 50, 572 pp., World Meteorological Organization, Geneva, Switzerland.

BOX 1.1: The Stratospheric Ozone Layer and its Role in the Atmosphere.

About 90% of the atmospheric ozone resides in the stratosphere, in a region between roughly 15 and 35 km above the Earth's surface, as indicated by the red line in Box Figure 1.1-1. This region is referred to as the stratospheric ozone layer. The remainder of the atmospheric ozone resides in the troposphere, the lower

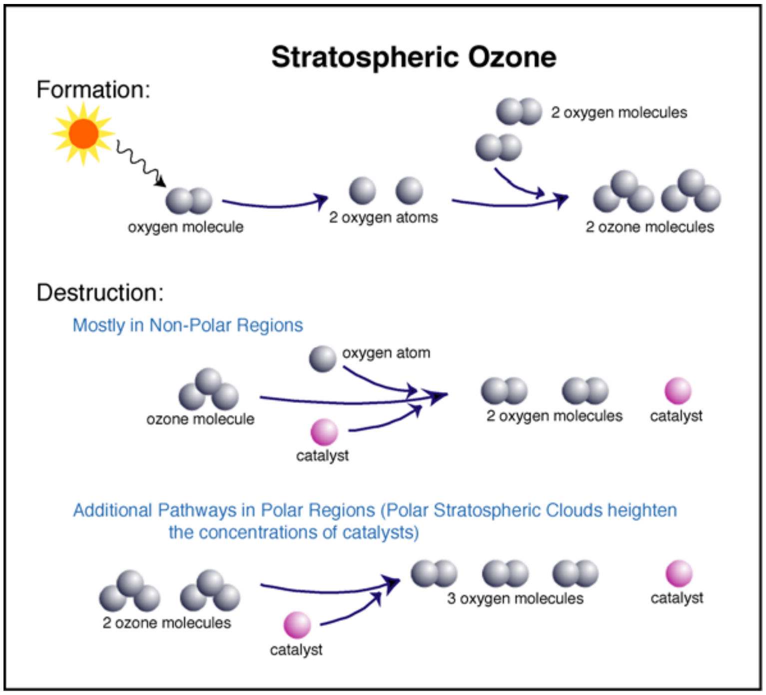


Box Figure 1.1-1 This figure shows the distribution of ozone in the atmosphere. (Adapted from Fahey, 2007)

layer of the atmosphere. Stratospheric ozone is formed and destroyed by chemical reactions, as shown in Box 1.2. Of particular note are the need for higher-energy UV radiation for the formation of ozone and the catalytic nature of the ozone removal processes. The ozone layer in turn shields the lower part of the atmosphere and the surface from damaging UV radiation because ozone itself absorbs UV radiation. Depletion of the ozone layer allows more UV- radiation (wavelength 280 to 315 nanometers) to reach the Earth's surface. This radiation is harmful to humans and many other biological systems and causes damage to materials. The ozone in the lower atmosphere, the troposphere, is formed by methods different from those in the stratosphere, as shown in Box 1.2. Further, the contribution of this lower atmospheric ozone to the total in the atmosphere is small, of the order of a few percent in the southern hemisphere to about 10% in the northern hemisphere. The ozone in the lower atmosphere is harmful because, in direct contact, ozone is toxic to biological systems and can deteriorate many materials. It can cause respiratory and other health problems for humans. In addition, ozone and its changes in both the stratosphere and the lower atmosphere are important greenhouse gases and thus their changes influence climate. See Appendix A of this Synthesis and Assessment Product for further background information about ozone.

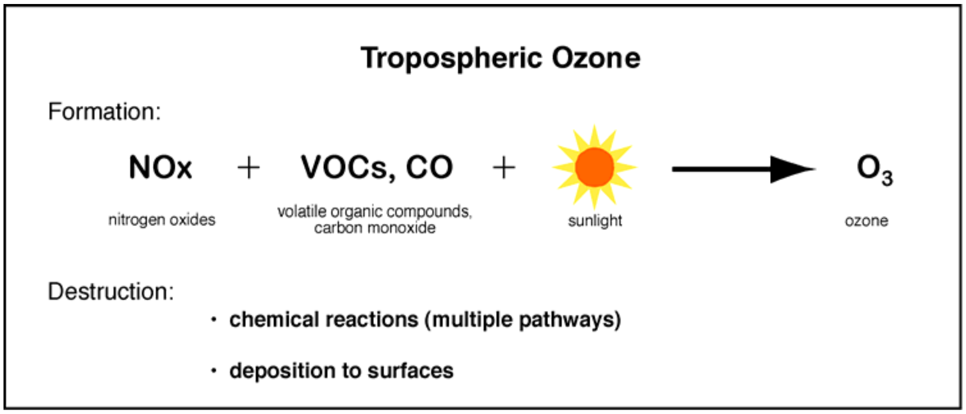
END BOX 1.1 ***************

BOX 1.2: A Simplified Representation of the Production and Removal of Ozone in the Atmosphere - the Processes that Determine the Abundance of Ozone.



Box Figure 1.2-1 Highly simplified representation of the chemical processes that lead to the production and removal of ozone in the stratosphere. See Chapter 3 and Appendix A for further details.

Oxygen molecules (O_2) are broken apart by the harsh UV radiation in the stratosphere to produce atomic oxygen, which reacts further with oxygen molecules to make ozone (O_3). The ozone in the stratosphere is removed predominantly via catalytic chemical reactions that regenerate the catalysts. The catalysts include atoms and radicals produced in the stratosphere from the breakdown of various chemicals emitted at the Earth's surface. They include naturally occurring chemicals such as nitrogen oxides and hydrogen oxides, as well as human-emitted chemicals containing chlorine and bromine atoms, such as chlorofluorocarbons (CFCs) and bromine-containing halons that are used as fire extinguishants. These human-emitted species, referred to as ozone-depleting substances (ODSs), are of concern for the depletion of the ozone layer. The destruction pathway marked "non-polar regions" in Box Figure 1.2-1 is predominant outside of the springtime polar regions, while the pathway marked "polar regions" is dominant in the springtime polar ozone depletion including the Antarctic ozone hole. Because of the nature of these chemical processes, as discussed above, a very small amount of the catalyst (for example, chlorine atoms from CFCs) can destroy a large amount of stratospheric ozone. In addition to these chemical processes, transport of ozone (redistribution) is key to determining the abundance of ozone in a given location.



Box Figure 1.2-2 Schematic representations of the chemical processes that lead to the production and removal of ozone in the troposphere.

In contrast to the stratosphere, in the troposphere ozone is made using near UV and visible radiation (*i.e.*, longer wavelength) because the higher energy, harsh UV (shorter wavelength) is screened out by the stratospheric ozone layer. This tropospheric ozone production process requires nitrogen oxides, mostly from combustion, and volatile organic compounds. Unlike stratospheric ozone, tropospheric ozone is removed not only by chemical reactions but also by other processes including contact with the surface. The transport of ozone from the stratosphere to the troposphere is important as an ozone source in certain regions.

******END BOX 1.2 *************